Astronomical Tides and Turbulent Mixing in ROMS/TOMS

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LONG-TERM GOALS

The long-term goal of this effort is to improve the Navy community ocean circulation model ROMS/TOMS by incorporating astronomical tidal forcing and the latest developments in turbulent mixing.

OBJECTIVES

The principal objective of this research is to improve subgrid-scale parameterization in Navy community and operational ocean circulation models. This is to be accomplished by assessing and refining turbulent mixing parameterization as well as including comprehensive direct astronomical tidal forcing of importance to many semi-enclosed marginal seas.

APPROACH

The approach is to incorporate latest developments in turbulence and tidal research and modeling into ROMS. This project complements well, the AESOP program, the ONR DRI on subgrid-scale parameterization and skill assessment of numerical ocean models as well as the new Characterization and Modeling of Archipelago Strait Dynamics (CMASD) DRI. Using the Adriatic Sea ROMS/TOMS as the test bed, we will incorporate direct astronomical forcing of the 11 major tides in the global ocean: semidiurnal M_2, S_2. N_2, K_2; diurnal K_1, O_1, P_1 and Q_1; long period Mf, Mm and Ssa. The co-oscillating barotropic tides will be prescribed from LHK's tidal model of the Mediterranean Sea (see *ocean.colorado.edu/ ~kantha*). Note that many global ocean models such as the ones resulting from NASA initiatives do not perform well in some marginal seas and it is essential that a regional model be used. Note also that compound tides such as M_4 will be generated by the nonlinear model itself and is an indirect result of the principal astronomical tidal forcing.

The latest Kantha and Clayson (2004) turbulent mixing model based on second moment closure is being incorporated into ROMS/TOMS. This model includes the effect of surface waves. No other turbulence model does at present. The inclusion of surface wave effects especially Stokes production of turbulence should greatly improve the simulation of the state of the upper ocean and hence drifter trajectories in the Adriatic.

Nonlocal mixing effects due to large eddies in the mixed layer are particularly important when convection dominates mixing. However, a rigorous incorporation of nonlocal effects is a daunting task that is not easily amenable to simplification. Nevertheless, this approach must be explored fully since parameterizations in the past have been rather ad-hoc.

WORK COMPLETED

Mixed layer models incorporated into ocean circulation models such as ROMS are either bulk models (e.g. Large et al. 1994) or based on simplified second moment closure of turbulence (e.g. Mellor and Yamada 1982, Kantha and Clayson 1994, 2004). While the bulk models appear to yield reasonable results, with appropriate tuning, for first moment quantities such as the mixed layer temperature, they are quite ad-hoc and lack the ability to provide information on second moment parameters such as the TKE and its dissipation rate, which can be verified against microstructure measurements. Second moment closure models do and hence provide an additional measure of model skill. However, most second moment closure formulations to-date have ignored non-local effects, which are clearly important under free convection dominated mixing scenarios. How best to incorporate non-local effects, replace the down-the-gradient approximation (DGA) for turbulent diffusion terms in the equations for the second moment quantities, and yet keep the problem tractable has been our major focus in the preceding year. Acquiring the means to assess any improvements resulting from this and the inclusion of Stokes production of TKE has been a secondary focus.

Observational data to compare with ocean models, especially on turbulence, are scarce. Microstructure measurements have not become a routine staple of oceanographic measurements as CTD casts have been for decades. Therefore, in collaboration with Dr. Sandro Carniel of ISMAR, Italy, who had a related NICOP grant from ONR, we participated in NATO Undersea Research Center/Naval Research Laboratory (NURC/NRL) DART 06A and 06B cruises in March and August of 2006, and collected turbulence data using a microstructure profiler constructed and operated by Dr. Prandke. The NURC also undertook an air-sea interaction study called Lasie07 in the Ligurian Sea in June 2007. Since we ourselves lack the huge resources to mount such a multi-ship campaign, where all relevant air-sea fluxes, including solar insolation, are measured and both the OML and ABL are probed with CTD and microstructure casts and radiosondes, in order to be able to partake of the resulting rich data stream well-suited to the verification of a mixed layer model, we participated in the week-long cruise on board the Italian CNR RV Urania. Unfortunately, nature did not cooperate and while strong winds and high sea state existed on the way to and back from the moored buoy site where, the intensive observations took place, the winds were weak and the sea state calm over the entire week we were on station! Also because the water column was deep at the site, we were unable to make microstructure measurements with an upward-traversing probe so that the wave-affected upper few meters of the water column, which is crucial (Kantha and Clayson 2004) for testing the efficacy of including Stokes production of turbulence on turbulent mixing in the upper layers, could not be sampled.

Turbulence data in the upper few meters of surface wave affected mixed layer are only a handful. We know of only one such set of measurements made with an upward-traversing microstructure probe at a 50m deep station in the Baltic Sea by Lass and Prandke (2003) from August 30 to September 7, 2001. We are trying to get hold of this data set to test the efficacy of including Stokes production in mixed layer models, especially since wave measurements were also made along with ADCP and CTD measurements at the site. We plan to test the Kantha and Clayson (2004) model against this dataset to assess the impact of Stokes production.

The upcoming tasks include the assessment and refinement of turbulence parameterization in ROMS/TOMS. The latest Kantha and Clayson (2004) turbulent mixing model, which accounts for Stokes production and is based on second moment closure, is being incorporated into ROMS/TOMS and we regard this task to be simpler than the assessment of resulting improvement in subgrid scale parameterization per se, mainly because of the lack of self-consistent observational dataset for comparison. The next task is to incorporate non-local model as described below.

We will work on incorporating astronomical tidal forcing into ROMS/TOMS in the third year of this project. Using the Adriatic Sea ROMS/TOMS as the test bed, we will incorporate direct astronomical forcing of the 11 major tides in the global ocean: semidiurnal M_2, S_2. N_2, K_2; diurnal K_1, O_1, P_1 and Q_1; long period Mf, Mm and Ssa. The co-oscillating barotropic tides will be prescribed from LHK's tidal model of the Mediterranean Sea (see *ocean.colorado.edu/ ~kantha*).

RESULTS

DGA for turbulent diffusion terms, i.e., third order moments (TOMs), is not only inelegant in concept but inaccurate in practice, since it severely underestimates them. One way to overcome this problem is to close the turbulence equations at the third moment level. But this requires modeling the fourth order moments (FOMs). Cheng et al. (2005) have recently reexamined the modeling of FOMs and have derived expressions for FOMs, which have nonzero cumulants related to vertical integrals of TOMs. The new FOMs are non-local in nature and in broad agreement with LES and aircraft data. The resulting TOMs have even simpler expressions and more importantly, are devoid of singularities. Cheng et al. (2005) simulated the convective PBL with the new TOMs and showed that the results agree very well with LES data. However, their approach would require the solution of 4 additional PDEs (for $\overline{u^2}, \overline{w^2}, \overline{w\theta}$ and $\overline{\theta^2}$) in addition to the two PDEs (for the TKE $q^2/2$ and its dissipation rate ε, or equivalently the turbulence velocity scale q and length scale ℓ) solved in two-equation second moment closure-based turbulence models incorporated into ocean models. The question is whether a simpler model can be constructed to yield roughly similar results.

It can be shown that to incorporate non-local effects, level 2.5 Mellor-Yamada model (Mellor and Yamada 1982), which is a two-equation model solving for q and ℓ must be abandoned, and a Level 3 model used instead (Nakanishi 2001, Cheng et al. 2002 and Clayson et al. 2004). This involves an additional PDE for $\overline{\theta^2}$. Thus incorporating non-local effects necessarily increases the computational burden in ocean models.

If we write $\overline{uw} = -\frac{q^2}{B_1}\tau S_M \frac{\partial U}{\partial z};\ \overline{w\theta} = -\frac{q^2}{B_1}\tau S_H \frac{\partial \Theta}{\partial z}$, where S_M and S_H are stability functions, and put $S_M = S'_M + S''_M$ and $S_H = S'_H + S''_H$, where primes denote the Level 2.5 model, and double primes the counter-gradient terms, it can be shown (Clayson et al. 2004) that

$$S'_H = \frac{A_2\left[1-\left(6A_1/B_1\right)\right]}{1-3A_2\left[6A_1+B_2\left(1-C_3\right)\right]G_H};\ S'_M = A_1\left\{\frac{\left[1-(6A_1/B_1)-3C_1\right]+9\left[2A_1+A_2(1-C_2)\right]S'_H G_H}{\left(1-9A_1A_2G_H\right)}\right\}$$

$$S''_H = \left\{\frac{3A_2(1-C_3)G_H}{\left(1-18A_1A_2G_H\right)}\right\}\left(C_\theta - B_2 S'_H\right);\ S''_M = \left\{\frac{9A_1\left[2A_1+A_2(1-C_2)\right]G_H}{\left(1-9A_1A_2G_H\right)}\right\}S''_H$$

where $\tau = B_1 \ell / q$ is the turbulence time scale and $C_\theta = \frac{\overline{\theta^2}}{\ell^2 \Theta_z^2}$;

$G_M = -B_1^2 (\tau S)^2; S^2 = \left(\frac{\partial U}{\partial z}\right)^2; G_H = -B_1^2 (\tau N)^2; N^2 = g\alpha\left(\frac{\partial \Theta}{\partial z}\right)$, and A_i, B_i and C_i are universal constants. Then the three-equation Level 3 turbulence model becomes:

$$\frac{D(q^2)}{Dt} - \frac{\partial}{\partial z}\left(S_q q\ell \frac{\partial (q^2)}{\partial z}\right) = 2(P + B - \varepsilon) ; \qquad \frac{D(\overline{\theta^2})}{Dt} - \frac{\partial}{\partial z}\left(q\ell S_\theta \frac{\partial (\overline{\theta^2})}{\partial z}\right) = -2\overline{w\theta}\frac{\partial \Theta}{\partial z} - 2\frac{\overline{\theta^2}}{\tau_\theta}$$

$$\frac{D(q^2 \ell)}{Dt} - \frac{\partial}{\partial z}\left(S_\ell q\ell \frac{\partial (q^2 \ell)}{\partial z}\right) = \frac{(q^2 \ell)}{q^2}\left(E_1 P + E_3 B - E_2 \varepsilon \zeta\right)$$

where $P = -\overline{uw}\frac{\partial U}{\partial z} - \overline{vw}\frac{\partial V}{\partial z} = q\ell S_M\left[\left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\partial V}{\partial z}\right)^2\right]$ is the shear production, $\varepsilon = \frac{q^3}{B_1 \ell}$ is the dissipation rate of TKE and ζ is the wall function. Note that $\overline{w\theta}$ can be written as $\overline{w\theta} = -q\ell S_H\left(\frac{\partial \Theta}{\partial z} - \gamma_c^\theta\right)$, where the second term denotes the counter-gradient term (Deardorff 1972, Large et al. 1994, Cheng et al. 2002). In the above formulation $\gamma_c^\theta = -\left(\frac{S''_H}{S'_H}\right)\Theta_z$.

Figure 1 shows comparison of the Level 3 model (and the conventional Level 2 ½ model) with LES data from Mironov et al. (2000). The improvement is however slight and suggests that further refinements are needed, perhaps abandonment of the DGA.

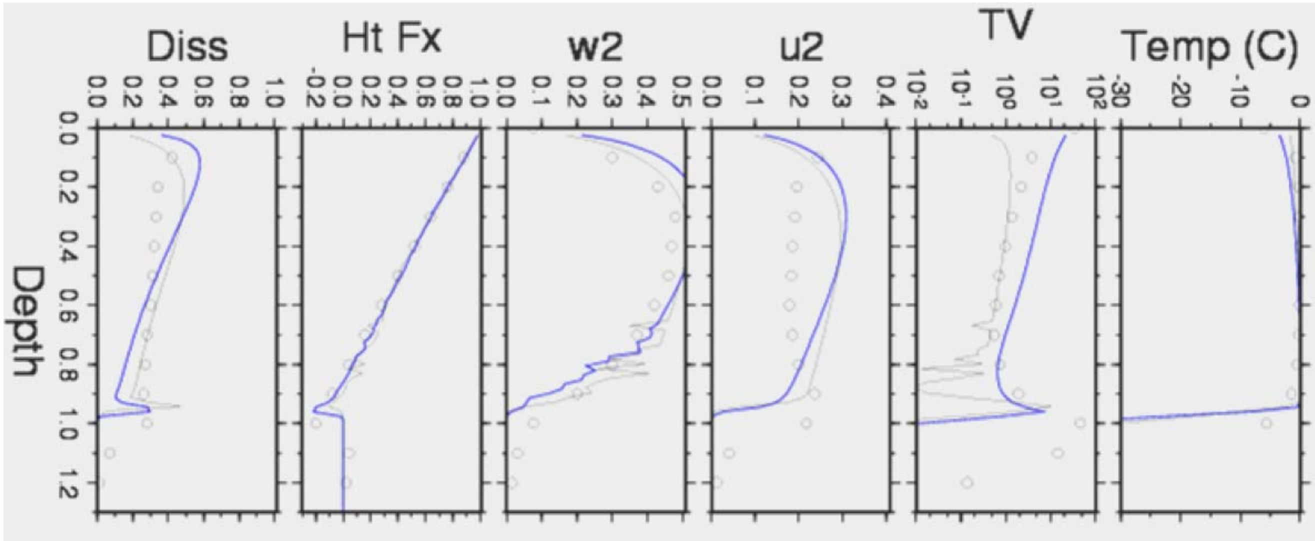

Figure 1: The distribution in the mixed layer of normalized quantities: from left to right, a) Dissipation rate, ε/B₀, b) Buoyancy Flux, B/B₀, c) vertical velocity variance, d) horizontal velocity variance, e) temperature variance, and f) temperature, (Θ-Θmax)/θ*. Blue curve shows the three-equation Level 3 non-local model and the black curve the two-equation Level 21/2 local model. Circles denote data points from Mironov et al. (2000).

For applications to ocean mixing, it is necessary to carry additional PDEs for $\overline{s^2}$ and $\overline{\theta s}$. In addition, the turbulence diffusion terms in all these equations must be dealt with suitably, with the DGA replaced by formulations making use of algebraic expressions for TOMs (e.g. Canuto et al. 2001). However, it is not yet clear whether it is absolutely essential to carry additional PDEs for turbulence quantities such as $\overline{u^2}, \overline{v^2}, \overline{w^2}$ and $\overline{w\theta}$ as Canuto et al. (2005, 2007) have done, which would increase the computational burden immensely. Ad-hoc formulations such as that of Mailhot and Benoit (1982) and Large et al. (1994) for the counter-gradient term $\gamma_c^\theta = c_0 K_H \frac{(\overline{w\theta})_0}{w_* D_m}$ are less expensive but also less attractive. There is also the question of whether there should be a cutoff gradient Richardson number Ri_c beyond which turbulence is extinguished. Experimental studies and recent theoretical (Galperin et al. 2007) and numerical (Canuto – personal communication) work suggest that there is no such cutoff but current second moment closure models (Kantha and Clayson 1994, 2004, Kantha 2003, Cheng et al. 2002) all have finite cutoff values and this issue also needs to be addressed in the coming years.

IMPACT/APPLICATIONS

Accurate depiction of many quantities of interest to worldwide naval operations, such as the upper layer temperature and currents, requires accurate simulation of turbulent mixing in the water column and accurate tidal forcing. Operationally, this contributes to better counter mine warfare capabilities through better and more accurate tracking of drifting objects such as floating mines. Other drifting materials such as spilled oil are also better tracked and counter measures made more effective. Other applications include search and rescue.

RELATED PROJECTS

Subgrid-scale Parameterization in 3-D Ocean Models: The Role of Turbulent Mixing (PI - Dr. Sandro Carniel of ISMAR, Venice, Italy) – NICOP.

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